Manufacturing Process Control and Optimization of CIGS on Flexible Substrates

M. E. Beck[1], J. VanAlsburg-Westermann[1], D. Mason[1], R. G. Wendt[1], S. Wiedeman[1], I. Eisgruber[1], J. Muha[1], C. Gambill[1], N. Gomez[2], R. Butcher[1], B. Huntington[1], G. Jensen[2], B. Joshi[2], and J. S. Britt[1]
[1]Global Solar Energy L.L.C., 5575 S. Houghton Rd., Tucson, AZ 85747, Phone: (520) 546-6313, Fax: (520) 546-6318
[2]ITN Energy Systems, Inc., 8130 Shaffer Pkwy, Littleton CO 80127, Phone: (303) 420-1141, Fax: (303) 420-1551

ABSTRACT

Global Solar Energy (GSE) has made significant advances in process control and optimization for the deposition of thin film $CuIn_{1-x}Ga_xSe_2$ (CIGS) onto flexible substrates in a roll-to-roll (RTR) manufacturing process. Improvements include controlled and uniform delivery of the constituent metals, Se, and an Na-containing precursor over the entire width and length of the web. Further, study of two metallic substrates has revealed that deposition conditions need to be optimized independently for each substrate. To date, the best laminated, large-area cell has yielded an NREL-verified AM 1.5 conversion efficiency of 9.2%, and a flexible module has been confirmed at $\eta = 8.15\%$.

1. Introduction

Continuous RTR processing of CIGS-based PV on flexible substrates is commercially attractive due to reduced manufacturing costs and the versatility of the resulting lightweight product. GSE has developed the equipment required for all-RTR production and optimized both equipment and processes to achieve significant improvements in yield and efficiency. Particular emphasis has been placed on the multi-source coevaporation of the CIGS absorber layer, described elsewhere [1]. Issues addressed include, but are not limited to, sensor development, efficiency improvements via Na incorporation, and increased CIGS-to-substrate adhesion, as well as optimized material utilization.

2. Process Control

Controlled delivery of film constituents to the substrate is essential to achieving uniform absorber composition as a function of web width as well as web length. In cooperation with ITN, GSE has developed and successfully implemented an in-situ x-ray fluorescence (XRF) sensor for metal composition feedback control [2]. In addition, GSE has developed a novel in-situ sensor to allow precise Se delivery. Typical control signals from both sensors are shown in Figure 1. The signals from the heat-up and cool-down phases have been omitted, leaving the signal from 240 ft. of CIGS deposition. Also shown is the signal obtained from a recently incorporated sensor for direct rate control of the Na-containing precursor.

While Figure 1 demonstrates the degree of control over the respective constituent delivery, Figure 2 illustrates the cross web compositional uniformity as a function of web position. The notations 2 in., 6 in. and 10 in. refer to data taken at 2, 6, and 10 inches from the reference edge of the 12.5 in.-wide web.

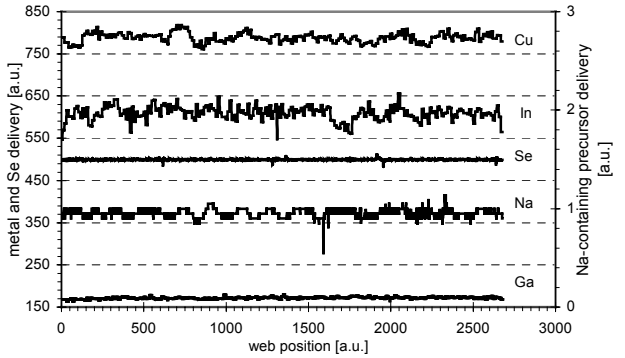

Fig 1. Metal, Se, and Na-containing precursor control as a function of web position

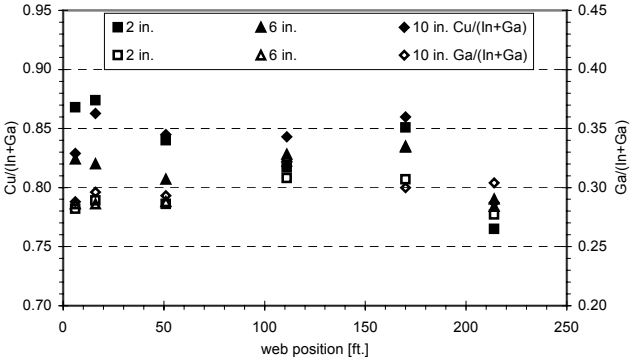

Fig 2. CIGS composition as determined by 20 kV EDX

3. Process Optimization

Next we needed to establish the optimum process parameters for each of the two metallic substrates under investigation. The quantitative response variables of interest were the device PV parameters and adhesion of the absorber to the back contact. Due to the lack of resolution and poor reproducibility typical of tape pull tests, adhesion was determined using a method and tester developed in house; this allowed for quantitative adhesion measurements as summarized in Table 1.

CIGS adhesion to the substrate was found to be a function of substrate type and deposition parameters. The data clearly shows type B substrate to be superior to type A under conditions 1 and 2. Adhesion improved for both types upon implementing condition 2, with the increase for type A more substantial. Implementing condition 3 yielded a further adhesion gain for type A, while type B exhibited a significant drop. Incorporation of Na into the absorber resulted in reduced adhesion for both substrate types at the 10 to 14% level.

Table 1. Average CIGS-to-substrate adhesion for two different metal substrate types

substrate	condition	no Na [psi]	with Na [psi]
A	1	3188	
B	1	5498	
A	2	3860	
B	2	5640	
A	3	5476	4921
B	3	3252	2806

Device efficiency was found to be directly proportional to CIGS adhesion, clearly showing that process conditions need to be optimized independently for each substrate type. Employing the optimized process parameters, the same maximum diode efficiencies, in the 11-12% range (total area = 0.68 cm^2), were obtained for substrate types A and B. However, CIGS-based device arrays prepared on the two substrates exhibited different device uniformity characteristics, as shown in Figure 3.

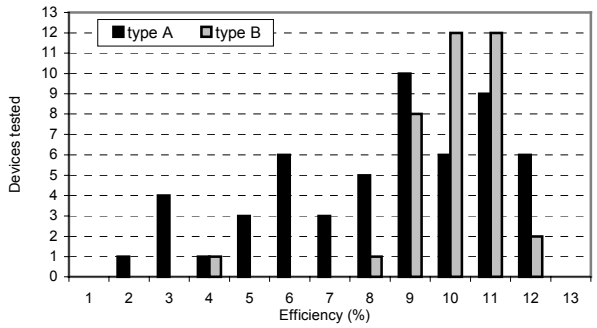

Fig 3. Diode efficiency distribution for two different metal substrate types. Total device area = 0.68 cm^2

The influence of the Na-containing precursor on material properties and device performance has been the subject of additional studies. Research at the IPE and at the ZSW on flexible metallic substrates has shown that Na incorporation yields improved V_{oc}, with resulting improvements in device efficiency [3]. However, there appeared to be an optimum amount of Na above which no further improvements were obtained [3].

Device data acquired on both substrate types currently under investigation at GSE revealed that for certain process conditions the incorporation of Na yielded device improvements. However, under optimized growth conditions no difference was observed at various Na levels. The latter might be related to different impurity levels in the absorber due to a change in substrate out-diffusion.

To date, the best laminated, large-area cell (total area = 64.4 cm^2) has yielded an NREL-verified AM 1.5 conversion efficiency of 9.2% (V_{oc} = 549.8 mV, J_{sc} = 28.97 mA/cm^2, FF = 57.5%) while a flexible 1050.6 cm^2 module was confirmed at η = 8.15% (V_{oc} = 8.786 V, I_{sc} = 1.813 A, FF = 53.7%). A graph of these results appears in Figure 4.

CIGS deposition by coevaporation of the elements typically employs a Se to metal excess of 3 to 5 × [4]. Recent research at GSE led to the conclusion that a Se/M-ratio of 1.2 to 1.7 is sufficient, thus improving Se utilization 1.8 to 4.2 times.

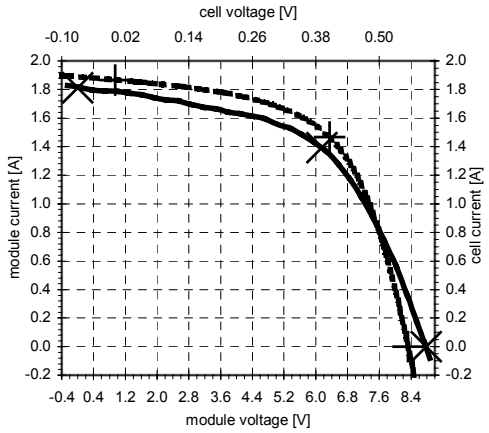

Fig 4. Official NREL AM 1.5 I-V curves of (a) 64.4 cm^2 cell, and (b) 1050.6 cm^2 module on flexible metal substrate

4. Conclusions

GSE has successfully developed and implemented in-situ sensors that enable controlled delivery of the absorber constituents onto flexible substrates in a RTR multi-source coevaporation process. Conditions allowing for uniform and reproducible deposition of high-quality CIGS onto two types of flexible metallic substrates have been identified. In addition, Se utilization has been significantly improved since a Se/M ratio in the 1.2–1.7 range was found to be sufficient. Further device improvements are possible and current data suggest that substrate out-diffusion and Na incorporation are the most promising areas for investigation.

5. Acknowledgements

The authors would like to acknowledge funding support from NREL Contracts ZAX-8-17647-11 (PVMaT), ZAK-8-17619-04 (TFP), DARPA Agreement MDA972-95-3-0036, and Unisource Energy. The valuable discussions and technical support provided by personnel at the Institute of Energy Conversion (IEC) are also gratefully acknowledged.

6. References

[1] J. Britt, S. Wiedeman, D. Mason, and R. Wendt. "High Rate CIGS Processing on Flexible Substrates," in *Proceedings of 2000 NCPV Program Review Meeting*, April 16-19, 2000, Denver, CO, pp.95-96.

[2] I. Eisgruber, B. Joshi, N. Gomez, J. Britt, and T. Vincent. "In-situ x-ray fluorescence used for real time control of $CuIn_xGa_{1-x}Se_2$ thin film composition," submitted to *Thin Solid Films*, July 2001.

[3] M. Hartmann, M. Schmidt, A. Jasenek, H. W. Schock, F. Kessler, K. Herz, and M. Powalla. "Flexible and Light Weight Substrates for $Cu(In,Ga)Se_2$ Solar Cells and Modules," in *Proceedings of 28th IEEE PV Specialists Conference*, September 17-19, 2000, Anchorage, AK, in print.

[4] A. M. Gabor. "*The Conversion of $(In,Ga)_2Se_3$ Thin Films to $Cu(In,Ga)Se_2$ for Application to Photovoltaic Solar Cells*" (Dissertation, University of Colorado, Denver) 1995.